

The peculiar dust shell of Nova DZ Cru (2003)

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ABSTRACT

We present *Spitzer Space Telescope* observations of the “peculiar variable” DZ Cru, identified by Rushton et al. (2008, MNRAS, 386, 289) as a classical nova. A dust shell, on which are superimposed a number of features, is prominent in the 5–35 μm range some 4 years after eruption. We suggest that the dust in DZ Cru is primarily hydrogenated amorphous carbon in which aliphatic bands currently predominate, and which may either become predominantly aromatic as the dust is photo-processed by ultraviolet radiation from the stellar remnant, or more likely completely destroyed.

Key words: circumstellar matter – novae, cataclysmic variables – stars: individual: DZ Cru

1 INTRODUCTION

DZ Cru (also known as Nova Cru 2003 and the “peculiar variable” DZ Cru) was discovered in 2003 August (Tabur & Monard 2003). It was initially reported as a nova but spectroscopic observations gave rise to doubts about its nova status, and comparisons were drawn with the unusual variable V838 Mon (Della Valle et al. 2003). Rushton et al. (2008) presented 1–2.5 μm infrared (IR) spectra obtained $\sim 1 - 1.5$ years after discovery. They found H I, O I and [N I] emission lines superimposed on a hot dust continuum and concluded that DZ Cru was indeed a classical nova at distance ~ 9 kpc (although this is subject to considerable uncertainty).

Here we present observations of DZ Cru with the *Spitzer Space Telescope* (Werner et al. 2003; Gehrz et al. 2007), that reveal a hot dust shell with unusual emission features.

2 OBSERVATIONS

DZ Cru was observed with the Infrared Spectrograph (IRS; Houck et al. 2004) on *Spitzer* in staring mode on three occasions, as detailed in Table 1. Spectra were obtained with both low- and high-resolution modes, covering the spectral range of 5–38 μm , and the blue peak-up array was used to centre the object in the IRS slits. For the high-resolution modes we also obtained observations of the background. The spectrum was extracted from the version 12.3 processed pipeline data product using SPICE version 2.2 (Spice 2009).

We discuss primarily the low-resolution data in this paper, and use the high-resolution data (which will be presented in detail elsewhere) to determine expansion velocities; the gas-phase features will also be discussed elsewhere. The spectra are shown in Fig. 1.

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Table 1. *Spitzer* observational log.

UT at mid-observation (YYYY/MM/DD.DD)	Programme	AOR Key	Time from outburst (d)	Observing time (s)	Dust flux (10^{-13} W m $^{-2}$)
2007/09/05.86	30076	22269952	1477	2692	9.8
2008/02/25.46	40060	17734912	1650	698	7.9
2008/04/21.33	30076	17735168	1706	1783	7.7

3 DISCUSSION

The spectral energy distributions (SED) are clearly dominated by dust, with emission features due to [Ne III] ($15.5\ \mu\text{m}$) and [O IV] ($25.9\ \mu\text{m}$), and dust emission features, superimposed; [Ne II] at $12.8\ \mu\text{m}$ is not present, to a limit of 2.7×10^{-18} W m $^{-2}$. We discuss the deduced expansion velocities, the dust emission, and the dust features in turn.

3.1 Expansion velocities

The FWHM of the (gas-phase) emission features indicate a velocity of $800 - 1000\ \text{km s}^{-1}$, assuming Doppler broadening of the lines. The *Spitzer* derived values are broadly in agreement with the velocities reported by Rushton et al. (2008) on the basis of line widths in the $1-2.5\ \mu\text{m}$ range. The presence of [Ne III] $15.5\ \mu\text{m}$ and [O IV] $25.9\ \mu\text{m}$ emission is common in mature novae (Lynch et al. 2008; Schwarz et al. 2008); this, together with the inferred expansion velocities, appear to reinforce the conclusion of Rushton et al. (2008) that DZ Cru is a classical nova.

If we assume that the O I and [O IV] lines arise in the same region of the ejecta (and given the time interval between the ground-based and *Spitzer* data, this assumption may be not be valid), we can assess whether the ejecta speed has changed over the ~ 1000 day period covered by our data. The velocities (deconvolved for instrumental resolution) derived from the O I $1.317\ \mu\text{m}$ line (Rushton et al. 2008) and the [O IV] $25.9\ \mu\text{m}$ line in our high-resolution *Spitzer* data over the ~ 4.5 yr period of our data satisfy

$$V_{\text{exp}} = 1480 (\pm 300) - 0.37 (\pm 0.23) t(\text{days}), \quad (1)$$

which indicates no significant variation with time. Thus we adopt the assumption that the velocity is constant, and we take the mean value $\bar{V}_{\text{exp}} = 1030 \pm 110\ \text{km s}^{-1}$ for the period covered by our observations.

3.2 Dust temperature and flux evolution

We have limited information about the state of the stellar remnant and of the ejecta at the time of our *Spitzer* observations. However it is evident that the SED of the dust is not well represented by a black-body, and we fit the 2007 September data using DUSTY (Ivezić & Elitzur 1997). We suppose that the stellar remnant is a black-body with temperature 10^5 K, the emitting dust is amorphous carbon with optical constants from Hanner (1988), the dust shell consists of $0.2\ \mu\text{m}$ grains, has an r^{-2} density distribution and an optical depth at $0.55\ \mu\text{m}$ of 0.1 (see Evans et al. 2005, for the rationale for these values, to which the output is not highly sensitive).

The temperature at the inner radius of the dust shell of

the DUSTY model that best fits (by eye) is 450 K; the fit, normalized to the dust emission for 2007 September (day 1477) at $10.1\ \mu\text{m}$, is included in Fig. 1. Assuming an absolute bolometric magnitude of -8.3 for DZ Cru (Rushton et al. 2008), the output from DUSTY indicates that the inner radius is at distance $\sim 7.5 \times 10^{13}$ m from the stellar remnant. This implies that the dust-bearing material was carried out at velocity $\sim 580\ \text{km s}^{-1}$, significantly slower than the oxygen-bearing material (Equation (1)), but comparable with velocities reported ($\sim 500\ \text{km s}^{-1}$) by Della Valle et al. (2003) about 2 days after discovery.

The flux from the dust shell, f , integrated over the wavelength range $5-35\ \mu\text{m}$, is given in Table 1, although as we have no data outside this range the values given are lower limits; nonetheless the flux clearly declines over the time of our *Spitzer* observations (see also Fig. 1). For a free-flowing expansion, constant L_* and conservation of grains, we expect $|\delta f/f| \sim 2 \delta t/t$. Within the uncertainties, the decline in the dust flux (Table 1) is consistent with this expectation and, therefore, with the assumption of constant expansion velocity. We also note that Rushton et al. (2008) estimated dust temperature 690 ± 40 K (620 ± 50 K) in 2005 February (June); the decline in temperature from 2005 to the *Spitzer* observations in 2007-8 are also consistent, within the uncertainties (and further noting that the dust temperatures in Rushton et al. are not black-body), with a free-flowing expansion.

It is not straightforward to compare the dust flux with the outburst flux as both luminosity at maximum and distance are poorly known. Using the values for absolute magnitude at maximum (-8.3) and distance (9 kpc) from Rushton et al. (2008) we estimate that the un-extinguished nova flux at outburst was $\sim 6.5 \times 10^{-11}$ W m $^{-2}$, some two orders of magnitude higher than our estimated dust fluxes in Table 1.

The length of time for which strong emission by the dust shell has persisted is unusual for a classical nova: the dust is still emitting strongly after ~ 4.5 years. By contrast, in the case of the archetypical dusty nova V705 Cas, the dust shell – prominent in the first two years after eruption (Mason et al. 1998; Evans et al. 1997, 2005) – was not detected with the Infrared Space Observatory ISO some 950, 1265 and 1455 days (~ 4 years) after outburst, to 3σ limits of 0.8 Jy in the wavelength range $5-12\ \mu\text{m}$ (Salama et al. 1999).

One possible explanation might be that the material ejected in the 2003 eruption has decelerated, “snow-ploughing” into circumstellar material that pre-dated the eruption. Such a scenario might be plausible if there were evidence for a decrease in ejecta velocity but as already noted (see Equation (1)), there is no such evidence. In addition, interaction between fast-moving ejecta and dense circum-

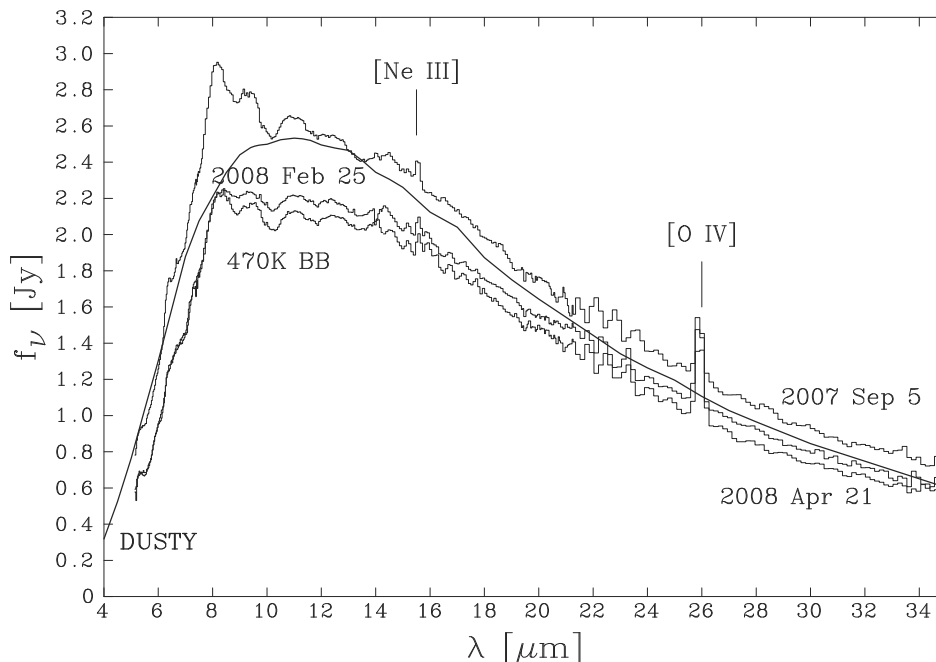


Figure 1. The dust shell of DZ Cru on the dates shown. The curve labelled “DUSTY” (red) has been normalized to the 2007 September spectrum at $10.1 \mu\text{m}$. Gas phase emission features are identified. The “fringes” in the $20\text{--}24 \mu\text{m}$ region are instrumental artefacts.

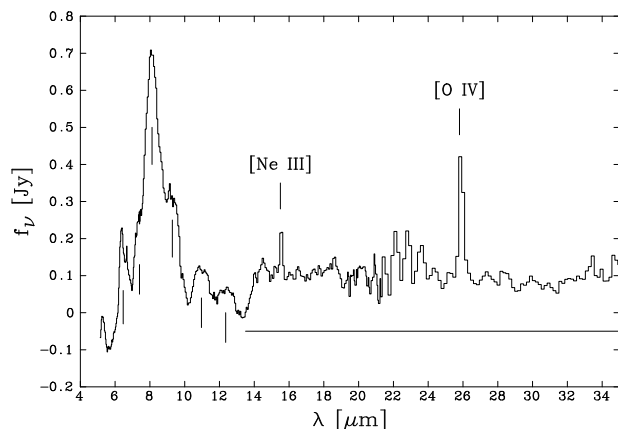


Figure 2. Dust features, obtained by subtracting the DUSTY MODEL from the 2007 September spectrum. Central wavelength and FWHM of features identified by vertical tick-marks are given in Table 2; the horizontal line indicate the approximate extent of the “plateau” feature.

stellar material would lead to shocked emission in the radio and X-ray bands, as in the case of GK Per (Sequist et al. 1989) and coronal emission in the IR. There is no evidence for either effect. Furthermore there is no evidence for any emission from the position of the progenitor in the 2MASS, MSX and IRAS surveys.

3.3 Dust emission features

There are superficial similarities between the dust shell of DZ Cru and those of V2361 Cyg (Helton et al., 2010, in preparation) and V2362 Cyg (Lynch et al. 2008, Helton et

al., 2010, in preparation). The latter displayed features at 6.37 , 8.05 , 11.32 , and a broad “plateau” centred at $\sim 18 \mu\text{m}$; Lynch et al. were unable to securely identify any of the dust features in V2362 Cyg.

We use the DUSTY fit (see Section 3.2 and Fig. 1) as a baseline to extract the dust features that are clearly present in DZ Cru. The result is shown in Fig. 2, in which the features are indicated by vertical ticks. The wavelengths and FWHM of the features are given in Table 2, together with an indication of their presence (possibly at slightly different wavelengths) or absence in V705 Cas (Evans et al. 2005) and V2362 Cyg (Lynch et al. 2008), and in evolved stars. In addition there may be a “plateau” of emission that extends from $\sim 14 \mu\text{m}$ to $\sim 34 \mu\text{m}$ (cf. Fig. 2), although the shape of this depends of course on the shape of the fitted DUSTY spectrum longward of $14 \mu\text{m}$. As is evident from Fig. 1, these features are present on all three dates of observation, but we note that the $8.2 \mu\text{m}$ feature in DZ Cru appeared to weaken in the 2008 February spectrum, only to recover somewhat by 2008 April. The features listed in Table 2 are significantly broader than the [O IV] and [Ne III] lines (FWHM $\sim 0.5\text{--}1 \mu\text{m}$, compared with $\sim 0.15 \mu\text{m}$ for the ionic lines), so it is unlikely that the features in Table 2 are ionic lines, or even blends.

We note that neither the $9.7 \mu\text{m}$ nor the $18 \mu\text{m}$ silicate features are present in the dust emission; furthermore, there is no evidence for the more structured $9.7 \mu\text{m}$ feature sometimes seen in cometary silicates (Wooden, Woodward & Harker 2004). We are therefore confident in ruling out silicates as a major dust component in DZ Cru.

Also, it seems unlikely that any of the features in Table 2 can be associated with silicon carbide, which displays a number of features in the $9\text{--}12.5 \mu\text{m}$ range, depending on the nature of the SiC (Speck, Thompson & Hofmeister 2005). No set of features for the materials studied by

Table 2. Dust features in DZ Cru in 2007 September; an “S” means that the feature is a “shoulder” on a main peak, “P”. Presence (✓) or absence (×) in the spectra of the novae V705 Cas and V2362 Cyg, and the post-AGB objects CRL2688 (Peeters et al. 2002) and HD100764 (Sloan et al. 2007), are also indicated; a – indicates no information.

λ (μm)	FWHM (μm)	S/P	V705 Cas	V2362 Cyg	CRL 2688	HD 100764	ID
6.46 ± 0.01	0.58 ± 0.03	P	–	✓	✓ (~ 6.3)	✓ (6.33)	UIR
7.24 ± 0.01	0.39 ± 0.02	S	–	–	×	×	–
8.12 ± 0.01	0.97 ± 0.02	S	✓	✓	✓ (8.22)	✓ (8.15)	UIR
9.29 ± 0.01	0.94 ± 0.02	P	×	×	×	×	–
10.97 ± 0.03	0.93 ± 0.06	P	×	×	×	×	–
12.36 ± 0.03	0.88 ± 0.07	P	×	×	×	×	–

Speck, Thompson & Hofmeister match those listed in Table 2.

4 UIR FEATURES

Despite the absence of the expected $11.25\,\mu\text{m}$ feature (but see below), some of the features in DZ Cru may plausibly be identified with “Unidentified infrared” (UIR; see e.g. Tielens 2008) features, which are seen in classical novae with optically thick dust shells (Mason et al. 1998; Evans et al. 2005; Evans & Rawlings 2008; Gehrz 2008). DZ Cru is the fourth dusty nova in which the “8.2- μm ” feature has been prominent (Mason et al. 1998; Evans et al. 2005; Lynch et al. 2008, Helton et al., 2010, in preparation). In the case of V705 Cas, Evans et al. (1997, 2005) identified the prominent feature at $8.2\,\mu\text{m}$ (cf. Fig. 2) as the UIR feature normally seen at $7.7\,\mu\text{m}$ (see also Geballe 1997; Mason et al. 1998).

Geballe (1997) classified the UIR features according to the strength of features in the $3\,\mu\text{m}$ and $6\text{--}13\,\mu\text{m}$ regions; novae seemed to occupy a unique category, with a $3.4\,\mu\text{m}$ feature that is strong relative to that at $3.28\,\mu\text{m}$. Further classification of the UIR features has been carried out by Peeters et al. (2002) and from the point of view of this paper, the classification of interest is their Class C. Objects in this class show no $7.7\,\mu\text{m}$ feature but instead a feature at $8.2\,\mu\text{m}$; moreover they also display a weak $6.4\,\mu\text{m}$ feature, and an extremely weak $11.25\,\mu\text{m}$ feature. These characteristics are very reminiscent of those seen in DZ Cru (cf. Table 2), and it is tempting to suggest that the UIR features in DZ Cru place it in Peeters et al.’s UIR Class C.

The two objects in Peeters et al.’s survey in their Class C are IRAS 13416–6243 and CRL 2688 (the “Egg” Nebula), both of which are post-AGB stars, the latter undergoing rapid evolution from the AGB to the planetary nebula phase (Cox et al. 1996). An object with a similar suite of UIR features is HD 100764, a first-ascent red giant with a dusty disc (Sloan et al. 2007). The central star of CRL 2688 has spectral classification F5Iae (effective temperature $T_{\text{eff}} \simeq 6370\,\text{K}$), while that of HD 100764 is an early carbon star with $T_{\text{eff}} \simeq 4850\,\text{K}$; the T_{eff} of IRAS 13416–6243 is $5440\,\text{K}$ (Peeters et al. 2002; Sloan et al. 2007). Other objects displaying similar UIR features have effective temperatures of this order (Sloan et al. 2007).

Investigation of UIR features in evolved and Herbig Ae/Be stars (Peeters et al. 2002; Sloan et al. 2007; Keller et al. 2008) strongly indicate that the wavelength of the “7.7” feature is highly environment-dependent, with a

clear dependence of wavelength on the effective temperature of the exciting star (Sloan et al. 2007; Keller et al. 2008). In stars having *lower* effective temperatures (e.g., as evidenced by direct spectroscopy, or by lack of circumstellar ionization) the “7.7” feature has a systematically *longer* wavelength; for example the “7.7” feature only appears at $7.7\,\mu\text{m}$ for $T_{\text{eff}} \gtrsim 10^4\,\text{K}$. Sloan et al. (2007) and Keller et al. (2008) attribute this to photo-processing of the UIR carrier by the stellar radiation field, and the consequent shift from aliphatic to aromatic bonds in the UIR carrier, which in novae is most likely a form of hydrogenated amorphous carbon (HAC; we note that, while Peeters et al. (2002) attribute the carrier to PAH molecules, this is not the case in classical novae (Evans & Rawlings 1994)).

If DZ Cru is a classical nova, its effective temperature ~ 4.5 years post-eruption would be well in excess of the values for AGB stars (cf. the estimated $T_{\text{eff}} \sim 10^5\,\text{K}$ for V705 Cas in Evans et al. 2005). There is ample evidence (e.g. from high excitation emission lines) for a strong ultraviolet radiation field in all four novae displaying the “8.2” feature. DZ Cru, and the other novae in which the “8.2” feature have been present, seem to defy the trend followed by other UIR-bearing objects. Furthermore, the UIR feature that normally appears at $11.25\,\mu\text{m}$ appeared at $11.4\,\mu\text{m}$ in V705 Cas (Evans et al. 2005), which is also apparently contrary to the trend of increasing wavelength with decreasing T_{eff} for the “11.25” feature (Keller et al. 2008).

The fact that the UIR features in DZ Cru and other novae are more akin to those in objects with a weak radiation field and late spectral type suggest that the distinctiveness of UIR features in novae is unconnected with the radiation environment. A likely explanation is that the UIR carrier in DZ Cru has only recently been exposed to the hard radiation field of the stellar remnant, possibly because it has been protected within dense clumps. Such clumps are required in nova winds to enable the chemistry that leads to nucleation (Evans & Rawlings 2008), so that the (hydrocarbon) dust they contain remains unaffected by the hard radiation field; there is certainly evidence for continued clumpiness in the (optical) remnants of the dusty novae FH Ser and RR Pic decades after eruption (Gill & O’Brien 1998, 2000). The UIR carrier in DZ Cru may therefore have only recently been exposed to the ultraviolet radiation field of the nova, thus limiting the photo-processing it has experienced.

5 CONCLUDING REMARKS

We have described the dust shell of the classical nova DZ Cru, which shows several broad emission features. A number of these features remain unidentified. However the “8.2” feature in DZ Cru and other novae may be associated with a UIR carrier in which aliphatic bonds predominate, likely as a consequence of the continued presence of dense clumps in the ejecta which shield the carrier from the hard radiation field of the nova. We anticipate that, as the ejecta (and clumps) disperse, a shift from aliphatic to aromatic may occur, accompanied by the shift of the UIR features to the blue; however it is more likely that the carrier will not survive exposure to the radiation. There are also implications for features in the $3\mu\text{m}$ -band, and it is unfortunate that spectra in this crucial region do not appear to have been obtained in the case of DZ Cru.

Continued IR spectroscopy of DZ Cru in the $3\mu\text{m}$ and $7\text{--}13\mu\text{m}$ regions would be valuable to observe the effects of dispersal on the UIR (and other) features.

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